FAECAL COLIFORM DECAY RATE IN WSPS OF PONTA NEGRA, NORTHEAST OF BRAZIL

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ABSTRACT
This paper presents the results for faecal coliform decay rates (K_b) in a real scale WSP system located in Natal-RN, northeast Brazil. The series comprises a primary facultative pond followed by two maturation ponds with a total area of 11 ha. The final effluent discharges into channels for infiltration in a 10 ha area. Influent sewage and the pond effluents were monitored weekly during a seven month period as a part of a major monitoring programme carried out on the WSP series and special attention was given to faecal coliform removal. Results showed that the K_b values predicted by the Marais equation assuming a hydraulic state of complete mixing overestimated faecal coliform die-off rates. K_b value adopted in the project design was 6.20 d^{-1} but the mean value found for the WSP system during the monitoring programme was only 0.85 d^{-1}. This value is below the recommended values in the literature for shallow ponds but similar to values for deep ponds. The sub optimal faecal coliform removal rate in the WSP system may be caused by the adoption of to high a K_b value at the design stage and the negative influence of high wind conditions on the mixing regime in the water columns of the ponds.
KEYWORDS: Faecal coliform decay rate (K_b), faecal coliform removal, hydraulic detention time, waste stabilisation pond.

INTRODUCTION

Waste stabilization pond series (WSPS) are efficient on removing pathogenic microorganisms, particularly in hot climate regions, due to the high ambient temperatures, luminosity, pH, and relatively long hydraulic retention times when compared to other treatment technologies. Researches in many countries have attested to the high efficiency of ponds on removing faecal coliform bacteria and estimated the bacterial decay rate (K_b). However, K_b values were generally obtained in pilot-scale pond systems which may differ from those found in real scale systems.

WSPS when well designed, operated and maintained, may produce high quality effluents meeting the WHO guidelines for unrestricted irrigation. In the semi-arid regions of Northeast Brazil, the high quality effluents may be the only available water resource for irrigation. However, WSPS are often not properly designed, operated and maintained and, as a consequence, their effluents still have a large concentration of pathogenic microorganisms which put at risk the health of the workers and consumers.

The WSPS of Ponta Negra (11 ha) was commissioned in 2000 and is currently treating around 60% of its total flow capacity. Previous results showed that its performance in terms of organic matter and faecal coliforms removal is below those expected, probably due to the use of overestimated decay rates for both BOD and coliforms on design stage. Moreover, the adverse impact of strong wind velocities during daylight hours throughout the year is considered to be at least partly implicated on poor performance (Meneses *et al* 2005; Pearson *et al* 2005; Saraiva *et al* 2005).

This paper aims to study the removal of faecal coliforms in more detail and compares the empirical equations for Kb with the real values found by means of a specific hydraulic model and discusses the reasons for the differences between the real and projected Kb used in the design.

MATERIAL AND METHODS

The WSPS was designed to treat the sewage of 33,500 habitants (8,208 m^3/day) and comprises a primary facultative pond (PFP) followed by two maturation ponds (MP-1, MP-2) (Table 1, Figure 1). The final effluent is discharged in channels for infiltration over an area of 15 ha of sandy soil.

Table 1. Physical characteristics of the Ponta Negra WSPS.

Characteristics	PFP	MP-1	MP-2
Length (m)	445	196*	234*
Width (m)	118*	143	122
Depth (m)	2.0	1.5	1.5
Area (m^2)	52,570	28,040	28,600
Volume (m^3)	105,138	42,057	42,899

* Mean values (all ponds have a trapezoidal shape).

Routine monitoring was based on weekly collection of grab samples of raw sewage and pond effluents during a seven month period (January to July 2004). Samples were taken at 7:00 to 8:00 h and analysed, according to APHA (1998), for faecal coliforms, pH, temperature, suspended solids, dissolved oxygen, total and soluble DBO_5, total and soluble COD. Chlorophyll *a* determinations followed the method described by Jones (1979). Flow rate was measured daily with an automatic flow meter comprising a PROSONIC transmitter and ultrasonic level sensor, models FMU 86-R1B1A1 and FDU 80 RG1A, respectively, installed on the Parshall flume.

RESULTS AND DISCUSSION

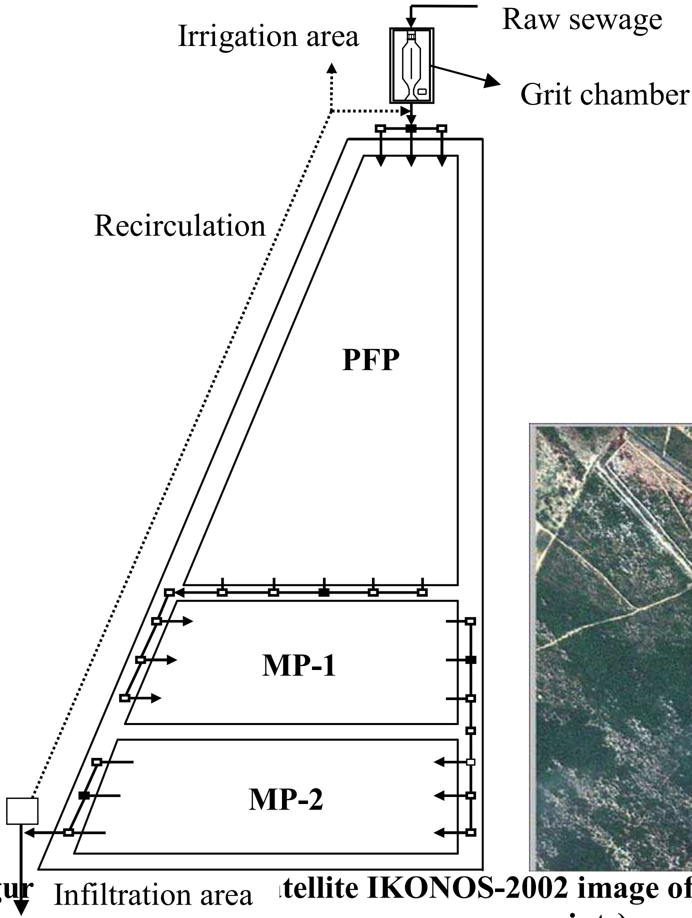
Operational characteristics

The mean flow rate during the monitoring period was 4742 m^3/day, corresponding to only 58% of the maximum design flow rate (8,208 m^3/day). The mean temperature was 27°C, the mean monthly precipitation was 297 mm. Southeast direction winds predominated (85%), with mean velocity of 4.1 m/s. Higher velocities were observed from 10 to 14 hours (7.21 – 9.40 m/s) while through the night values were around zero. This behaviour generally caused a scum layer near the inlet of the PFP, by the morning, which disappeared as wind velocities increased and mixed the water column.

Hydraulic detention time (HDT) and organic loadings were based on the influent flow rate plus the recirculation flow rate from the final effluent to primary facultative pond (57 m^3/h) resulting in a mean value of 6110 m^3/day. HDT of 17.2, 6.8, and 7.0 days were estimated for facultative and maturation ponds (MP-1, MP-2), respectively, and the surface organic loadings were 296, 262, and 248 $kgDBO_5$/ha.day, respectively. For primary facultative pond, loading was in range generally used in projects, however, maturation ponds seems to be overloaded, which can be confirmed by high values of chlorophyll a, suspended solids and DBO e COD. Although life design period was not achieved the results attested that designing criteria for the WSPS were inadequate. Besides, the influence of wind velocity was not considered.

Raw sewage and effluents characteristics

Table 2 shows the means of variables monitored on raw sewage and pond effluents. After performing Shapiro-Wilks'W normality tests for all variables (Statsoft, 2006), the geometric mean was chosen as the central tendency for faecal coliform. The series removed 73% and 55% of BOD and COD, respectively. Soluble fraction of DBO and COD varied in the ranges of 20 to 27% and 29 to 33%, respectively, indicating that major part of the organic contents in pond effluents were associated with high algae attested by the high values of chlorophyll a, suspended solids.



Figur tellite IKONOS-2002 image of the Ponta Negra WSPS (■ Sampling points)

Table 2. Mean values for the parameters determined in raw sewage and pond effluents.

Parameters	**RS**	**PFP**	**MP-1**	**MP-2**
Temperature (° C)	28.9	27.8	28.1	28.0
pH	7.0	7.3	7.4	7.3
DO (mg/L)	-	4.2	4,8	4.0
BOD_5 (mg/L)	305	120	116	82
BOD_f (mg/L)	-	32	23	22
COD (mg/L)	577	338	319	259
COD_f (mg/L)	-	97	104	84
Suspended solids (mg/L)	364	421	324	241
Chlorophyll *a* (µg/L)	-	1825	1592	1104
Faecal coliform (FC/100ml)	5.53×10^7	3.03×10^6	4.84×10^5	5.99×10^4

Faecal coliform removal efficiency

Pond efficiencies were 92.94% (PFP), 84.03% (MP-1) and 87.62% (MP-2), resulting in an overall removal of faecal coliforms in the WSPS of 99.86%. Overloading may be one of the causes for poor efficiency on MP (less than 1 log unit per pond).

Adopting the same methodology and variables used by the designer of the WSPS, i.e. assuming complete mixing of the reactors, a Kb of 6.2 d^{-1}, and the actual operational conditions, the effluent concentrations should be 398,551 FC/100 ml (PFP), 9,234 FC/100 ml(MP-1), and 208 FC/100 ml (MP-2). These values are very different from those found during the monitoring period (Table 2), particularly for the final effluent (5.99 x 10^4 FC/100 ml) which is around 300 times higher than the predicted value of 208 FC/100 ml.

Anova analysis followed by Tukey Test for comparisons among means at a level of 0.05 showed that means for raw sewage are significantly different from those found in the pond effluents ($p < 0.05$). However, the means for pond effluents did not differ from each other attesting that maturation ponds were not efficient on coliform removal (Figure 2).

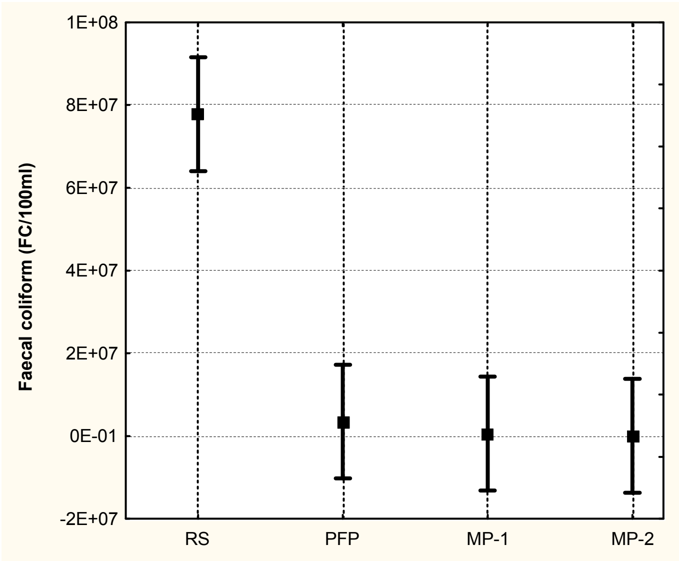


Figure 2. Confidence limits for the means of faecal coliforms in the raw sewage (RS) and pond effluents (means whose bars do not overlap are significantly different at a level of 0.05)

Meneses (2006) studying the hydraulic flow on Ponta Negra PFP with tracers, concluded that it tended to present a disperse flow. However, just for comparisons, on this work, the coliform decay rate was estimated using models for complete mixing, disperse flow, and plug flow, and compared with values found by means of empirical equation.

Dispersion numbers (d)

Dispersion numbers for the ponds (Table 3) were estimated by equations 1 (Polprasert and Bhattarai, 1985), 2 (Agunwamba *et al* 1992, simplified by Von Sperling 1996) and 3 (Yanez 1993). Because PFP has a trapezoidal form, the dispersion number was estimated as the mean of four sequential sections in the pond.

$$d = \frac{0.184 \times [t \times \upsilon(B + 2 \times H)]^{0.489} \times B^{1.511}}{(L \times H)^{1.489}} \quad (1)$$

$$d = 0.102 \times \left(\frac{3 \times (B + 2 \times H) \times t \times \upsilon}{4 \times L \times B \times H} \right)^{-0.410} \times \left(\frac{H}{L} \right) \times \left(\frac{H}{B} \right)^{-(0.981 + 1.385 \times H/B)} \quad (2)$$

$$d = \frac{L/B}{-0.26118 + 0.25392 \times (L/B) + 1.01368 \times (L/B)^2} \quad (3)$$

Where: L = length (m), B = width (m), H = depth (m), t = HDT (days), ν = cinematic viscosity (m^2/d).

Table 3. Dispersion numbers found in the ponds.

References	Dispersion numbers - d		
	PFP	MP-1	MP-2
Polprasert and Bhattarai (1985)	0.127*	0.566	0.322
Agunwamba *et al.* (1992)	0.810*	1.121	0.859
Yanez (1993)	0.387*	0.688	0.485

* Mean values for the four sections in the PFP.

Determination of actual Kb values

K_b values (Table 4) were estimated according to equations 4, 5 and 6 (Von Sperling 1996), respectively for complete mixing, dispersed flow and plug flow. Silva *et al.* (1996) found higher Kb values in shallow pilot scale WSPS (8 d^{-1} and 3 d^{-1} for PFP with λs < 350 kg/ha.day and 1.25 deep, and 1.0 deep maturation ponds, respectively). Values presented in Table 4 are inferior, but closer to K_b values obtained in deep pilot scale WSPS in northeast Brazil.

$$N_e = \frac{N_i}{1 + K_b \times t} \qquad (4)$$

$$N_e = N_i \times \frac{4 \times a \times e^{1/(2\times d)}}{(1+a)^2 \times e^{a/(2\times d)} - (1-a)^2 \times e^{-a/(2\times d)}} \; ; \; a = \sqrt{1 + 4K_b \times t \times d} \qquad (5)$$

$$Ne = Ni \times e^{-Kb\times t} \qquad (6)$$

Where: N_e = faecal coliforms in effluent; N_i = faecal coliforms in affluent; K_b = faecal coliform decay rate (d^{-1})

Table 4. Actual Kb values according to hydraulic flow model.

Pond	K_b (d^{-1})				
	Complete Mixing	Dispersed flow			Plug flow
PFP	0.77	0.20[a]	0.34[b]	0.27[c]	0.15
MP-1	0.77	0.44[a]	0.52[b]	0.47[c]	0.27
MP-2	1.01	0.45[a]	0.58[b]	0.50[c]	0.30

a, b, c – estimation of “d” according to Polprasert and Bhattarai (1985), Agunwamba *et al*. (1992) e Yanez (1993), respectively.

K_b values estimated by empirical equations

The empirical equations below were used to determine K values (for complete mixing conditions) and the results are presented on Table 5.

$K_{b(T)} = 2.6 \times (1.19)^{T-20}$ (Marais 1974) (7)

$K_{b(T)} = 1.1 \times (1.07)^{T-20}$ (Yanez 1993) (8)

$K_{b(T)} = 1.608 \times H^{-0.877} \times t^{-0.329} + [7.656 \times 10^{-4} \times H^{-3.674} \times t^{1.811} (L/B)^{1.509}] \times 1.07^{T-20}$

(Von Sperling 1999) (9)

$K_b = 0.712 \times (1.166)^{T-20}$ (Mills *et al* 1992) (10)

$K_{b(T)} = K_{b23} \times (1.07)^{Tair-23}$ (Andrade Neto 1991) (11)

Where: T = liquid temperature (° C); T_{air} = air temperature (° C); K_{b20} = 20°C decay rate (d^{-1}); K_{b23} = 23°C decay rate (d^{-1}).

Table 5. Empirical decay rate values for complete mixing flow.

Pond	K_b (d^{-1})				
	Complete Mixing				
	Marais (1974)	Yanez (1993)	Sperling (1999)	Mills *et al.* (1992)	Andrade Neto (1991)
PFP	5.89	1.51	0.67	1.08	6.46
MP-1	6.20	1.54	0.86	1.53	2.15
MP-2	5.40	1.46	0.81	1.36	2.15

Results above show that K_b values predicted by the Marais (1974) equation were an overestimation when compared to actual values presented in Table 4. A similar situation was observed when calculating the predicted value (viz. 6.46 d^{-1}) for PFP using the Andrade Neto (1991) equation. On the other hand values predicted by the Von Sperling (1999) equation were closer to the actual values assuming complete mixing.

K_b estimation for dispersed flow was based on the following equations and the results are presented in Table 6.

$K_{b(T)} = 0.917 \times H^{-0.877} \times t^{-0.329} \times (1.07)^{T-20}$ (Von Sperling 1999) (12)
$K_b = \ln[1.1274 x (0.6351) x (1.0281)^T x (1.0016)^{Cs} x (0.9994)^{\lambda s}]$ (Polprasert *et al* 1983) (13)
$K_b = 0.019 x 0.915^{(T-20)} e^{0.170 x I_m}$ (Xu *et al* 2002) (14)

Where: Cs = algal concentration (mg/L dry weight); λs = superficial organic loading (kgCOD/ha.day); Im = mean light intensity (J/cm^2.day).

The equations used to determine K_b under plug flow conditions are given below and the predicted values obtained are presented in Table 6.

$K_b = 0.50 x (1,02)^{T-20} x (1.15)^{2x(pH-6)} x (0.99784)^{(DBO_5-100)}$ (Saqqar and Pescod 1992 apud Kellner and Pires 1998) (15)
$K_b = 5.67 \times 10^{-4} (S_o/H) + 0.0135 \times pH$ (Mayo 1995) (16)
$K_b = 0.014 \times (1.034^{T-20}) + 5.7 \times 10^{-4} (S_o/H) - 0.0063 \times pH$ (Mayo 1995) (17)

Where: So = solar radiation on pond surface (cal/cm^2.day); BOD_5 = soluble BOD_5 (mg/L).

For dispersion flow conditions the Von Sperling (1999) equation once again gave predicted results close to the real K_b values shown in Table 4, whilst the Mayo (1995), equation 17, gave the best predicted values for plug flow conditions.

Design criteria for northeast Brazil

Table 7 presents K_b values obtained in pilot scale studied in northeast Brazil (Farias 1989; Oragui *et al* 1995; Silva *et al* 1996).

Table 6. Values of K_b estimated by different equations for dispersed flow and plug flow.

POND	K_b (d^{-1})					
	Dispersion flow			**Plug flow**		
	Von Sperling (1999)	Polprasert *et al.* (1983)	Xu *et al.* (2002)	Saqqar & Pescod (1992)	Mayo (1995)	
					Eq. 16	Eq. 17
PFP	0.36	0.29	-	0.91	0.36	0.24
MP-1	0.48	0.17	0.07	0.96	0.45	0.33
MP-2	0.45	0.13	0.14	0.93	0.45	0.33

Table 7. K_b values found in pilot scale WSPS in northeast Brazil as a function of depth, hydraulic detention time and organic loading (assuming complete mixing).

POND	Shallow ponds					Deep ponds			
	H = 1.75 TDH ≥ 2	H = 1.25		H = 1,0 TDH ≥ 5	H = 0,6 TDH ≥ 5	H = 2.2		H = 2,0 TDH ≥ 6	H = 2.3 TDH ≥ 6 λ_S = 250 a 400
		TDH ≥ 12 λ_S < 350	TDH ≥ 7 λ_S > 350			TDH ≥ 5	TDH ≥ 8		
Anaerobic	5.0	-	-	-	-	1.0	0.9	-	-
Primary facultative	-	8.0	3.0	-	-	-	-	-	1.5
Secondary facultative	-	1.0		-	-	0.5	0.3	1.2	-
Maturation	-	-	-	3.0	4.0	1.0	2.0	-	-

H (m); TDH (d); λ_S (KgBOD/ha.day)

CONCLUSIONS

The removal efficiency of faecal coliforms was well below the value predicted from design calculations and this may be associated with the use of a not properly flow model, a high K_b value, and a low organic loadings estimated on maturation ponds while in practice was observed an overloading.

The K_b value of 6.20 d^{-1} adopted in project design for all ponds in the series, assuming complete mixing, is higher than the observed mean value of 0.85 d^{-1}. K_b = 6.20 d^{1} is more convenient for use with shallow maturation ponds (depth < 1.25 m) with organic loadings of less than 350 kgBOD/ha.day on the primary facultative pond (Silva *et al.* 1996).

Assuming completely mixed conditions, K_b values predicted by the Marais (1974) equation are an overestimation while the equation of Von Sperling (1999) gives more realistic results. Considering dispersed flow, the Von Sperling (1999) equation, also produced better predicted results when compared to the real values obtained for the WSPS. The Mayo (1995) equation was better for a plug flow regime. Caution is advised when applying the Marais (1974) equation for estimating K_b values in very large ponds under strong wind conditions.

The value for K_b to be adopted should be coherent with the hydraulic flow model, the type of pond, and pond depth, and with the surface organic loading.

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